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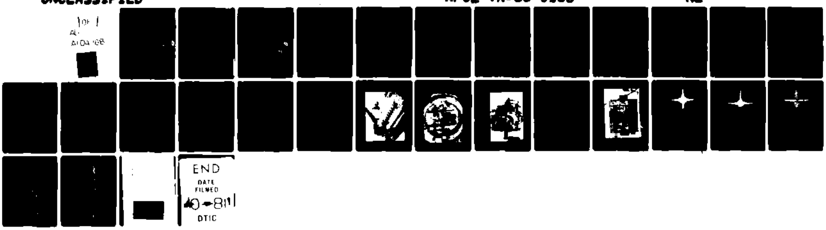

LEVEL II

AFGL-TR-81-0186

STRATOSPHERIC CRYOGENIC INFRARED BALLOON EXPERIMENT

A 0.1 cm^{-1} LN_2 Cooled Balloon-Borne Fourier Transform Spectrometer System

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A balloon-borne liquid nitrogen cooled Fourier transform spectrometer system was test-flown from Holloman Air Force Base on 8 October 1980. The system and the modifications to it required for balloon application are described and the flight results discussed. Samples of the interferograms obtained during the flight and their transforms are presented. Procedures for improving the performances on subsequent flights are discussed.

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Introduction

The infrared emissions by stratospheric gases and aerosols are of importance in the design parameters of military systems and, when measured and analyzed, provide information on the chemical composition of the stratosphere.

The infrared emission spectrum at stratospheric levels has been measured previously, but the increasing sophistication of military systems requires the measurement of the extremely low levels of radiation emitted by trace stratospheric species at ever higher resolutions and lower noise.

Given a suitable detector and electronics, the major factor limiting the NESR (Noise Equivalent Spectral Radiance) of an infrared system is the noise generated by non-signal photons on the detector. In many cases this radiation is thermal emission from the optical elements of the system itself. In such cases a distinct reduction of NESR can be achieved by cooling the system. A number of spectrometer systems have been constructed which, for this reason, are intended to operate with the entire instrument at cryogenic temperatures. These have included circular variable filter systems, grating spectrometers and Fourier transform spectrometers. One of the highest resolution cryogenically cooled systems is a 0.1 cm^{-1} resolution interferometer constructed for the Air Force Geophysics Laboratory by Idealab, Inc. This system has the potential, when suitably modified and incorporated into a balloon-borne system, of obtaining stratospheric emission data at low NESR levels and at higher resolution than any previous data. The major effort on this program was to; (1) perform the modifications to the instrument required for a high signal to noise ratio at stratospheric levels and for operation in a balloon flight environment, and (2) conduct flights utilizing this instrument and auxiliary systems on a balloon platform.

The construction of the interferometer represented a considerable technological advance. The solution of several of the technical problems encountered took longer than anticipated and caused a substantial delay in the completion of the unit.

After delivery of the unit to the University of Denver it was learned that the modifications required for satisfactory balloon flight performance and measurement of low stratospheric radiance levels were much more extensive

than anticipated. In spite of a very intensive effort these modifications further delayed the program so that only one test flight was possible during the period covered by this report. A description of the balloon-borne system and the flight results are given here.

Interferometer

The interferometer consists of a germanium coated KCl beamsplitter with movable and fixed cat's-eyes replacing the plane mirrors of a Michelson interferometer. The basic interferometer is shown in Fig. 1. The movable cat's-eye mirror assembly is the perforated cylindrical tube with the drive moter attached at one end. Figure 2 is a photograph of the instrument dewar with the end plate removed. The liquid nitrogen cryogen reservoir attaches to the bottom part of the flat plate, which supports the interferometer base plate. Infrared radiation enters the system through a ZnSe window in the vacuum dewar.

The original detector used with the interferometer was HgCdTe. It was used as the field aperture with the interferometer output radiation focused onto it by means of an off-axis parabola. In the original system as supplied by the manufacturer, only one cryogen (liquid N_2) was used and the detector was operated at 77°K. While this has a number of advantages from a construction standpoint, it has the disadvantage that at 77°K, HgCdTe is not background limited. As a result, cooling the interferometer did not improve the detector D* by the two orders of magnitude necessary for stratospheric measurements. (Vanasse, 1980). It was felt that since ultimate sensitivity was desirable it would be worthwhile to modify the unit for dual cryogen operation and use a liquid helium cooled detector. A major effort on this contract was the design and installation of a liquid helium dewar and fill system. This system has a 2 liter capacity and is shown in Fig. 3. A separate vacuum system to isolate the detector and LHe reservoir from the LN_2 environment was considered, but would have required major modification to the main cryostat. Instead, the vacuum of the main cryostat plus multi-layers of aluminized mylar superinsulation were utilized to reduce the heat load on the LHe reservoir below the 120 mw maximum permissible for a 10 hr LHe hold time.

In order to incorporate the unit into the space available it was necessary to modify the output optics. Figure 4 is a schematic of the optical system. The off-axis parabola focuses the output field onto an aperture

(maintained at LHe temperature) calculated to match the size of the central interference fringe for the shortest wavelength of interest. The radiation then passes through a bandpass filter and is collected onto the 2 mm x 2 mm Ge:Hg detector by conical light pipe.

(The vacuum achieved in the cryostat during initial tests was only marginally adequate for the LHe system. The cryostat was modified to provide larger pumping ports and to accommodate an external LN_2 vapor trap. An 800ℓ/sec Vac-ion pump was also installed in the cryostat.)

Laser fringes from a HeNe laser are used to trigger the interferogram sampling at specific increments of path difference. Previous cryogenic interferometer systems had operated the laser in the cryogenic chamber. This was accomplished only with a great deal of effort and after overcoming a number of major problems. In view of these difficulties, the manufacturer opted to leave the laser outside the cryogenic enclosures and transfer the laser radiation into the interferometer by means of an optical pipe. This has led to some unexpected problems which will be discussed below.

When the instrument is cooled to $77^{o}K$ the major infrared radiation emitter within the interferometer field of view is the window in the dewar. This window can potentially be the major source of background radiation noise, so that for ultimate sensitivity it should also be cooled. This presents some problems for a system operating in the atmosphere since several atmospheric species (H_2O, CO_2, etc.) will condense on the cold window unless some method is used to keep these gases from reaching the window. We have developed a system which cools the window with liquid nitrogen and uses the boil-off nitrogen gas to flush a baffle system extending in front of the window. This flow of dry nitrogen keeps the atmospheric gases from condensing on the window. This system will not work at low altitudes if the instrument is looking out horizontally or below. At high altitudes it can be operated at depression angles of at least 5^{o} without frost forming. An antifrost system for the instrument has been constructed. Since it is desirable to obtain data at elevation angles above and below the horizon, a system has also been constructed for raising and lowering the front-end of the dewar to achieve a suitable scan in elevation. For launch and low altitude operation the unit is run

at 10° in order to keep the window clear. Provision was made to change the elevation angle by command from the ground.

In addition to obtaining data on the emission of the atmosphere at high altitudes, the system will also be used to obtain high spectral resolution data concerning the radiation emitted by the earth. This is accomplished by moving a plane mirror in front of the interferometer so that rather than viewing the horizon the system views the nadir. Since the earth is a much more intense radiation source than the atmosphere, it is necessary to reduce the sensitivity in order to keep the preamplifier from becoming saturated. This is done by switching the detector bias voltage at the same time that the mirror is placed in front of the interferometer. Provision is also made to move an ambient temperature black body in front of the instrument on command in order to get an in-flight check on the calibration of the system.

Detector Electronics

Substitution of the Ge:Hg detector for the HgCdTe also made it necessary to replace the preamplifier and amplifiers used for producing a suitable signal from the detector. The high impedance of the Ge:Hg detector required that the capacitance of the leads coupling the detector to the preamplifier be small in order to maintain the system frequency response. Optimum interferometer performance also requires linear detector preamp response over at least 5 orders of magnitude in signal. These considerations forced the preamplifier to be located within inches of the detector and use of an operational amplifier configured preamplifier. Tests of available operational amplifiers yielded none that would operate at liquid nitrogen temperatures; they also showed degradation after being exposed to these temperatures. It was necessary therefore to provide heating to the preamp continuously when the instrument was cold or cooling. For this purpose a servo controlled heater was built into the preamplifier case. Since the total heat capacity of the liquid helium dewar was limited, it was necessary that the preamplifier be thermally isolated from the helium reservoir to avoid material reduction of the helium hold time. The original coupling was done with stainless steel wire, however, this proved to be too microphonic and had to be replaced by a subminature coaxial cable employing a manganin center conductor and teflon insulation.

Control Electronics

The electronics, as supplied by the manufacturer, were standard units used for ground-based operation of warm interferometers. For balloon-borne operation the units had to be repackaged since the construction provided neither a physically rugged nor thermally suitable configuration. In addition, operation of the interferometer cold changed several parameters in the control circuitry which made the performance marginal. This required redesign of several of the control circuit servos along with their repackaging.

Laser Housing

The laser tube requires a striking voltage of several kilovolts and a steady state supply of 1250 volts. This presents a potential for arc-over at the reduced ambient pressures encountered on a balloon ascent. The laser tube and power supply were therefore enclosed in a pressurized tube. The completed unit was tested for several hours on the bench in Denver and operated properly for several days testing at Holloman, but then developed an intermittent output flicker. Since installation of a new tube and power supply required removal of the pressure seals, it was necessary to test the unit after reassembly. The tests were performed in the environmental test chamber at HAFB and the unit was cycled through a complete ambient pressure and temperature profile similar to that encountered in an actual balloon ascent. The unit functioned properly although some decrease in intensity was noted during the ascent (probably a temperature effect). No indication of flickering or arc-over was found. The unit was therefore judged suitable for flight.

Data Handling

Handling the data generated by an interferometer is not a trivial task. Since obtaining the spectral information requires extensive mathematical manipulation of the data, digital data handling is essential. The interferometer signal consists of the detector voltage versus position of the moving mirror. As noted above, the detector signal must be linear over a wide dynamic range and the position of the mirror is monitored by the laser fringes. Digital sampling must be triggered by the fringes and the triggering does not necessarily occur at a uniform rate. Loss of a single data point destroys the spectrum derived from the interferogram.

The large number of data samples produced by the interferometer system during the course of a balloon flight and the rate at which these are generated exceed the capabilities of tape recorder systems suitable for balloon flight use. PCM Telemetry of the interferometer main data channel for ground recordings was, therefore, necessarily the prime data link. Interfacing the interferometer data with this system is complicated by the fact that the interferometer sampling and the PCM sampling occur at a non-synchronized rate.

Auxiliary Instruments

Two major emission bands due to atmospheric CO_2 lie wholly or partially within the frequency range spanned by the interferometer data. These bands are centered at 667 cm^{-1} and at 2350 cm^{-1}.

Two narrow band LHe cooled filter radiometers, one with a half power band with a 16 cm^{-1} centered at 2362 cm^{-1} and the other with a 3.5 cm^{-1} bandpass at 682.3 cm^{-1} were mounted on the gondola with their optical axis parallel in azimuth to that of the cold interferometer. These units were intended to obtain emission data complementary to that obtained with the interferometer.

In addition several parameters were monitored during the flight for diagnostic purposes and as an aid in analyzing the data. These included detector impedance, interferometer drive velocity, several cryostat temperatures, and laser intensity. The platform orientation in azimuth was monitored by an orthognal pair of magnetometer probes.

The data from these sources was recorded at 12 bit accuracy (i.e., 1 part in 4096) on an on-board tape recorder and at 8 bit accuracy (1 in 128) from the PCM telemetry.

Gondola

The gondola serves two basic functions; it provides a mounting base for the various components that compose the complete system and it provides protection for the components when they impact on the parachute after flight. The gondola for this system was constructed using designs which we have used successfully for many other payloads. The base of the unit is constructed of aluminum I-beams which have been found to give very good strength to weight ratios. For ease of mounting, a rectangular structure is used. The outside vertical framework is constructed of square conduit and employs diagonal crossmembers for rigidity. The completed system ready for flight is shown in Fig. 5 .

Flight Preparations

The total system except for the telemetry package was completed in August 1980 and testing of the unit was begun. The combination of high vacuum and cryogenic operation made testing a very slow process since it takes over a week to pump the unit to the required vacuum and cool it to 77°K. Thus a considerable amount of time was required to tailor the various servo circuits, and correct problems encountered in getting the system operational in a balloon flight configuration. Once this was accomplished the system was transported to Holloman AFB where integration with the AFGL PCM telemetry and balloon control systems was undertaken.

The AFGL PCM system outputs data words at precise time intervals, a requirement for ease of decoding by ground equipment. Interferogram samples must be taken at precise path differences which can be somewhat variable in time.

Feeding interferogram samples into the PCM system requires an interface which insures that one and only one valid data word is transmitted per interferogram sample. At the time the data system was designed, the sample rate was expected to be near the frame rate of the PCM encoder. Accordingly the data was intended to be transferred to the PCM through first-in-first-out buffers, clocked in by the end of conversion pulse from the analog to digital converter in the interferometer and clocked out by a strobe from the PCM encoder.

Considerable time was expended to get this system functioning reliably (tests were complicated by several of the factors noted below) until it was decided that, given the sample rate desired, the buffers were an unnecessary complication. They were bypassed for a more reliable system which utilized the PCM Strobe to clear the data word after reading it, ensuring that sampling by the encoder before the next interferometer sample was ready would result in transmission of an empty frame. Since the valid data rate was well below the PCM sample rate, this system gave excellent results.

The instrument was kept at 77°K during the period of testing and several operational problems became apparent requiring attention on their own as well as complicating the PCM tests. The turnaround position of the moving mirror carriage at the zero path difference (ZPD) end was erratic and it was not possible to get consistent performance out of the system. The large dynamic range requires the gain of the interferogram channel to be changed after the ZPD region.

The erratic turnaround resulted in missing the ZPD on some interferograms, and incorrectly changing the gain on others. A continual decline in the magnitude of the laser fringes also presented a problem. The laser signal amplitude would decline over a period of hours and readjustments of the laser position would never quite return the output to its previous level. The drive exhibited periods of instability particularly near the beginning of the scan. Attempts to correct these problems external to the dewar were unsuccessful and it was concluded that the problems were related to parameters inside of the dewar. As noted above, the turn around time for opening the dewar is quite long and time constraints on the program precluded doing this. While these problems significantly decreased the possibility of having a completely successful flight, it was felt that much would be learned about the potential of the system by performing a flight with the unit.

Accordingly the various instrument parameters were adjusted to provide maximum tolerance for drift while still providing good data. The laser amplitude was about 2V peak to peak. The instrument was flown on October 7, 1980.

Flight Results

The flight profile achieved was very similar to that programmed; an ascent at an average rate of 800 ft/min, approximately one hour at the float altitude of 102,000 ft, a gradual valve down to 80,000 ft, and termination. The basic interferometer system performed well (with the exceptions already noted on the ground) throughout this sequence. The laser controlled sampling for the main data channel of the PCM ceased about 20 minutes after launch. Sampling returned for a period while the instrument was at float altitude but was apparently controlled by noise rather than laser fringes. Analog data, although not usable for data processing, indicates the infrared signal channel was operating correctly. Properly sampled interferograms were recorded up to an altitude of 20,000 ft.

The signal channel incorporates an automatic gain ranging feature since the total radiation field, and therefore the amplitude of the ZPD signal, can be expected to vary by a large factor during the course of the flight. This circuit sets the overall gain for the succeeding scan on the basis of the

maximum signal generated during a scan. The gain is increased by a factor of two if the maximum signal does not exceed 30% of the available range and decreased, again by a factor of two, if the maximum signal exceeds 80% of full scale. A positional gain change fixed in magnitude also occurs at a fixed number of samples after the start of scan. This point is normally set to occur at a point beyond the ZPD where the modulation amplitude has diminished at least an order of magnitude below that of ZPD.

The variability of the starting point of the scan had effects on both of these systems. If the turn around occurred too early and ZPD was not traversed, the gain ranging circuit increased the gain for the next scan. If the turn around was too late, the positional gain change occurred before ZPD was traversed resulting in a saturated interferogram and also in a reduction of gain for the next scan. These effects will be noticed in Figs. 6 through 8 which are examples of the properly sampled interferograms obtained during the flight.

When properly adjusted for the various gain factors, the interferograms show a decrease with altitude which correlates with an increase in detector impedance, the expected result of the decrease in the total radiation field. The fractional modulation of the ZPD appears to have been constant indicating that interferometer alignment remained good and that all the main channel electronics were normal to the point where sampling ceased.

A moderate resolution (0.5 cm^{-1}) transform of an interferogram recorded at 16,000 ft is presented in Fig. 9 which includes the range from 600 - 1400 cm^{-1} showing the major emission features in this range due to CO_2, O_3, H_2O, and CH_4. Figure 10 is a portion of a full resolution transform demonstrating the 0.1 cm^{-1} resolution capability of the instrument.

The 682.3 cm^{-1} filter radiometer functioned from launch until power down which occurred during the parachute descent of the platform. Discussion of this data is included as an appendix.

The 2362 cm^{-1} unit failed shortly before launch, apparently as a result of vacuum problems.

Post Flight Analysis

The interferometer was tested warm (while still in the flight configuration) upon its return to Denver. The laser fringe amplitude was large enough to saturate the electronics, i.e., 25V P/P throughout the scan indicating that the final positioning, done just before launch, had been optimum and had remained so during launch, recovery, and transport to Denver. The drive was still erratic and the turn around variable. Tests with the cryostat opened indicated considerable friction on the movable cat's-eye ways particularly near ZPD, which accounts for the drive instabilities. The interferometer, still mounted on the base plate, was returned to Idealab for inspection and renovation. It was found that the movable cat's-eye ways and mounting were loose, as well as the "start of sampling" transducer being out of alignment and scraping. The interferometer is being completely disassembled and the ways reworked and recoated (essentially relubricated with a solid lubricant). The whole interferometer unit will then be reassembled and aligned before being returned to the University of Denver in preparation for future flights. The interferometer had not been aligned or lubricated for 4 to 5 years and it was due for reworking. Once the interferometer has been reworked, lubricated, and aligned, it should be ready for at least 4 or 5 years of balloon flights.

The sources of the major problems encountered prior to and during the flight have been identified and appropriate remedial action is in progress. The one exception to this is the gradual degradation of the laser fringe amplitude. We have normally experienced a large drop in fringe intensity when the unit is first cooled, but this can be regained within a few percent by slight adjustments in the external optical system. The long-term loss seems to be a function of time spent at LN_2 temperature, although it is difficult to imagine a mechanism that would continue once a stable cold temperature has been reached. The problem should not arise if the flight is launched within 10 days of cool-down, which is normal procedure. As insurance, a heater will be installed on the light pipe which can be activated if it is necessary to maintain the cool-down beyond 10 days.

The exact cause for the cessation of sampling at 20 K ft is not clear. The available evidence indicates either a further decline of the laser fringe amplitude, failure of the A to D converter, or of the laser preamplifier. The major argument against reduction in fringe amplitude as the cause lies in

the abrupt cessation of sampling. Gradual decline of fringe intensity would probably have resulted in a period of intermittant correct sampling interspersed with the random noise sampling before sampling ceased.

The system was sampling properly in post flight checks at Denver, so any problem with the electronics then must have been a result of the balloon environment (i.e., temperature). The interferometer electronics were all in a single insulated enclosure. Immediately prior to the end of sampling all electronics were functioning exactly as designed and, with the possible exception of the sampling circuitry, continued to do so throughout the flight. The A to D converter dissipates more power per unit area than most of the other devices in the electronics and therefore runs well above ambient, so that it is unlikely that it failed as a result of cooling. Failure due to overheating would probably have permanently destroyed the device.

In either case, reoccurrence of the problem will be prevented by, (1) laser fringe amplitude several times minimum required, (2) a complete environmental test of the electronics.

Summary

The flight test proved the potential of the interferometer as a balloon-borne instrument. The basic system withstood the rigors of preflight transport, launch, and balloon ascent without degradation in performance. The causes of problems existing prior to the flight (drive instability and turn-around variations) have been identified and presumably corrected. The sampling problem which terminated the recording of processable interferograms at 20,000 ft has been identified to within one of two possible sources and procedures for elimination of both of these devised. Enough data was obtained to demonstrate the capabilities of the unit as a balloon-borne high resolution spectral radiometer. Balloon flights with the reworked unit should result in data representing a distinct advance in our knowledge of the detailed emission characteristics of the stratosphere.

FIGURES

Appendix A

The LHSR Data

Flight Results

As discussed in the main body of the report, the 682.3 cm^{-1} filter radiometer functioned throughout the flight and excellent data was obtained.

The 2362 cm^{-1} developed a vacuum leak in the window seal and the resulting poor vacuum resulted in thermal coupling of the internal preamplifier to the LHe reservoir. No data was obtained.

The package was launched shortly after sunrise to take advantage of the lull in surface winds which normally occurs at this time of day. As a result the solar elevation angle coincided with the radiometer field of view or fell within the near field baffle system during a portion of the ascent. Although the solar radiation was strongly attenuated by atmospheric CO_2, the small fraction penetrating to the balloon altitude was sufficient to perturb the measurement (a transmission factor of 10^{-4} results in radiance levels comparable to atmospheric emission).

During this portion of the flight the gondola motion was such that the instrument traversed the solar plane in azimuth at intervals as short as 20 - 30 sec. This portion of the data requires editing to eliminate the portions influenced by solar radiation. (These peaks may also be the result of out of band rejection, which has not been checked below the 10^{-4} level.)

Data Reduction and Analysis

Once the data was converted to radiance values, temperatures measured on a rawinsonde run were converted to black body radiance values for comparison.

A major uncertainty in this approach is the result of measuring the temperature from a separate platform. The measurements therefore are not coincidental in time or space. Additionally an exact altitude register between the two vehicles must be determined. The model atmosphere lapse rate from 0 to 11 km is -6.5^{o}K km for comparison to $\pm 0.5^{o}$K the altitudes need to be in register to better than ± 0.08 kilometer. The ideal solution to these problems would be an independent temperature measurement from the balloon platform. Unfortunately these are subject to large errors due to thermal contamination by the balloon wake. Procedures for making accurate ambient temperature measurements from the balloon platform are being investigated.

The correlation between the 0800 rawinsonde run and the radiance temperatures is fairly good for the range from 450 mb to above 200 mb, although it appears that the fit could be improved significantly by a slight modification of altitudes for the balloon data.

There are large ($4^{o}K$ to $6^{o}K$) differences in the temperatures for points below 500 mb where the radiance temperatures are below that of rawinsonde. Some of this may reflect warming after sunrise. (The surface temperature changed from $11^{o}C$ at the time of launch of the main balloon to $15^{o}C$ when the radiosonde was launched.) The radiance data just before launch agrees with the $11^{o}C$ measurement. The lower radiance temperatures, however, persist to a greater altitude (26,000 ft) than short-term solar warming would be expected.

Additional meteorological data for the Tularosa basin area has been requested as an aid in evaluating the data through this region.

The noise level of the radiometer signal is equivalent to $\approx 2 \times 10^{-8}$ $w/cm^2/sr/\mu$. Portions of the data at float level were expanded and examined for spatial and temporial variations. Unfortunately a slight residual solar perturbation ($\approx 10^{-6}$ of the signal level) and the effect of the balloon altitude oscillation, which had not completely damped before valve-down was started, were sufficient to mask any other variations which might have been present. A data tape with radiance values as a function of time is being prepared. The pressure vs time values can be read from P.C.M. Telemetry tape at AFGL more accurately than they can be determined from the information supplied to DU.

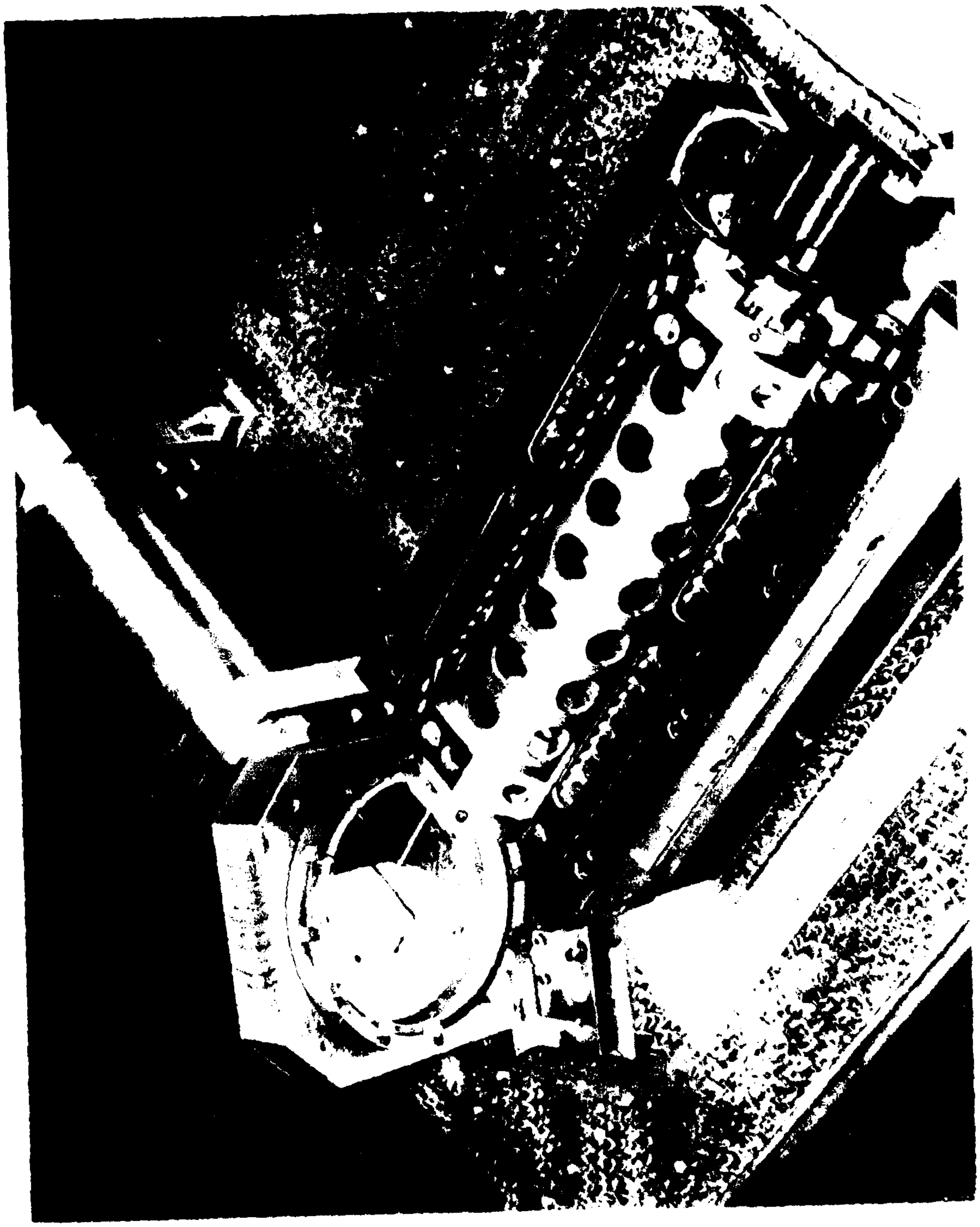


Figure 1

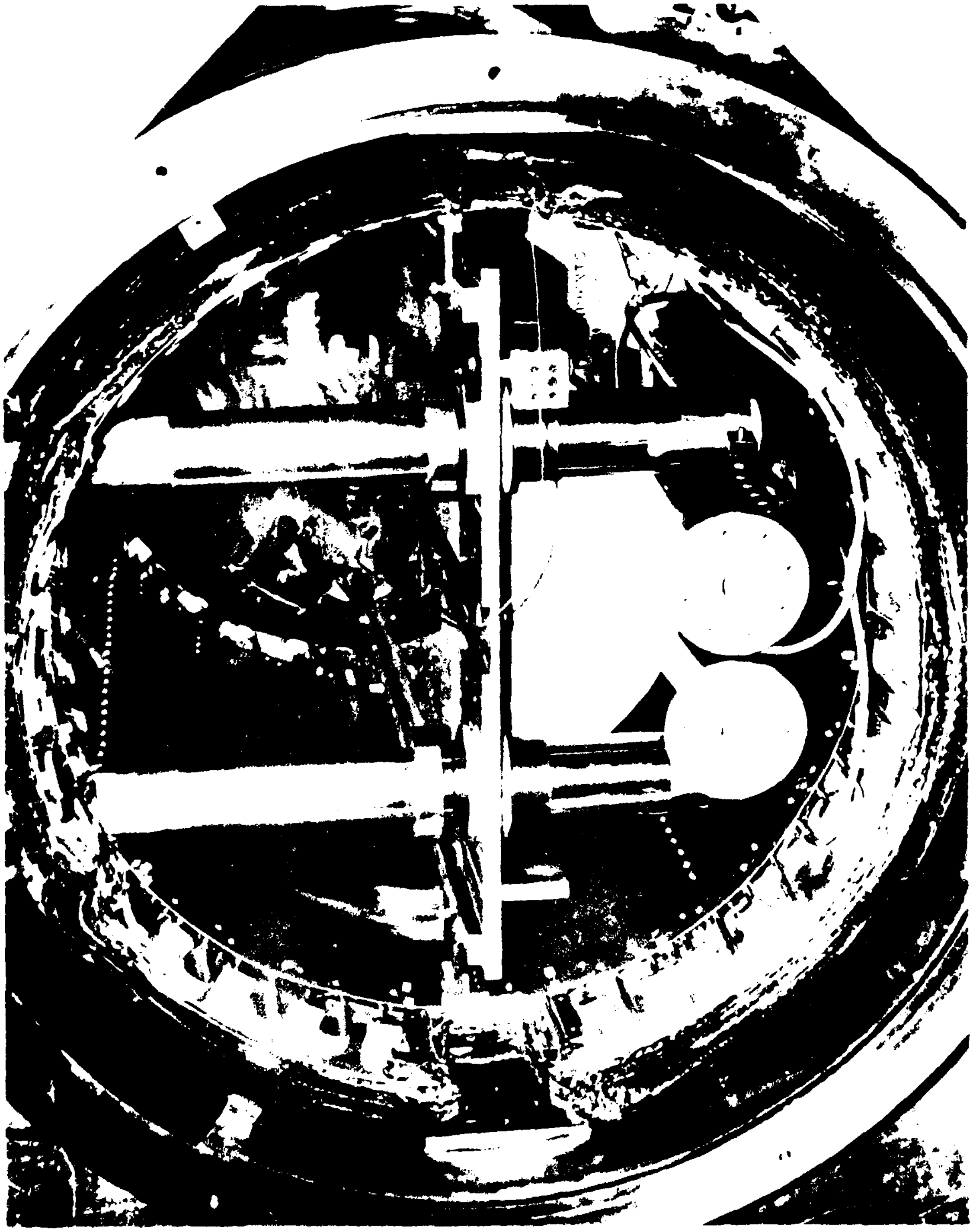
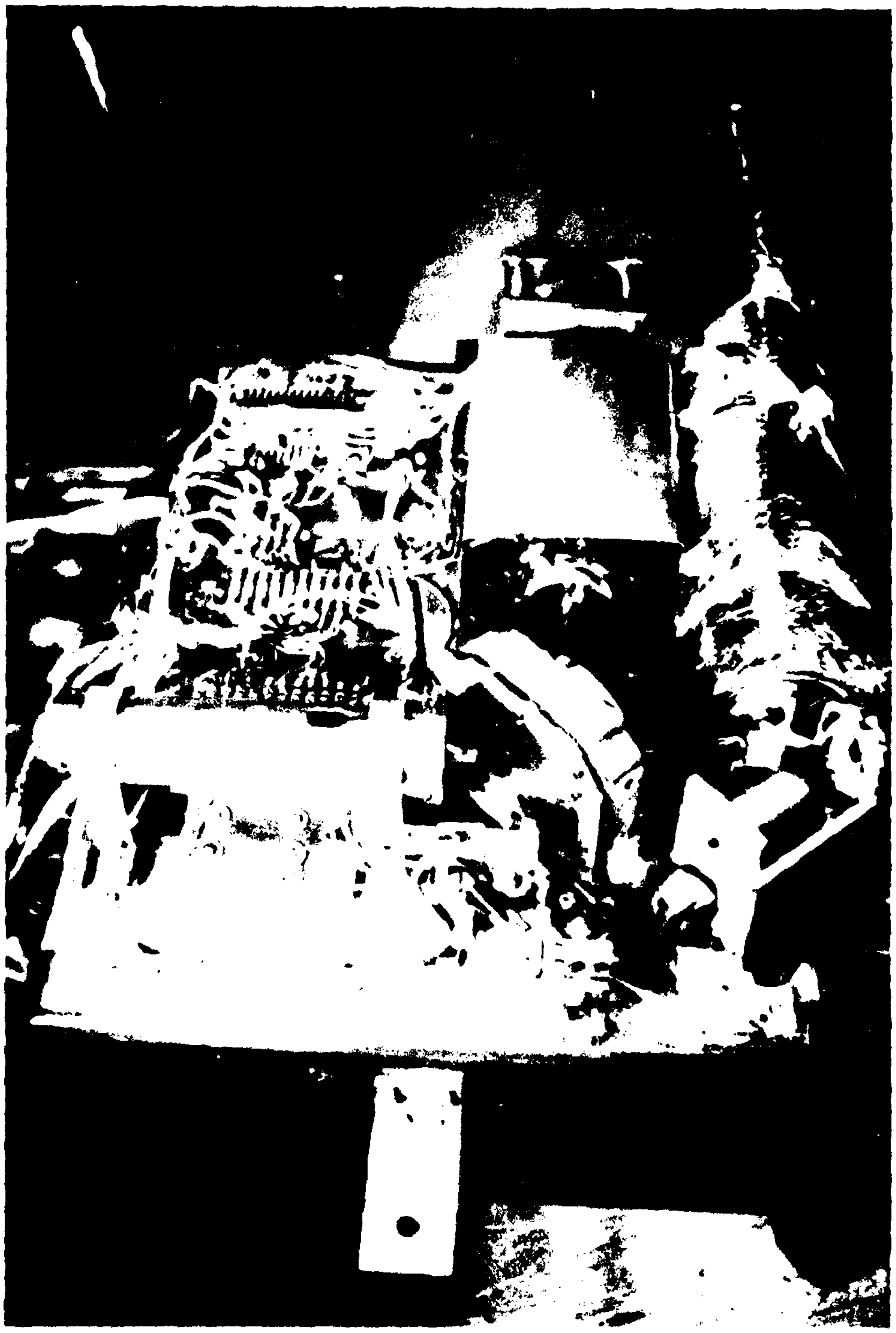


Figure 2



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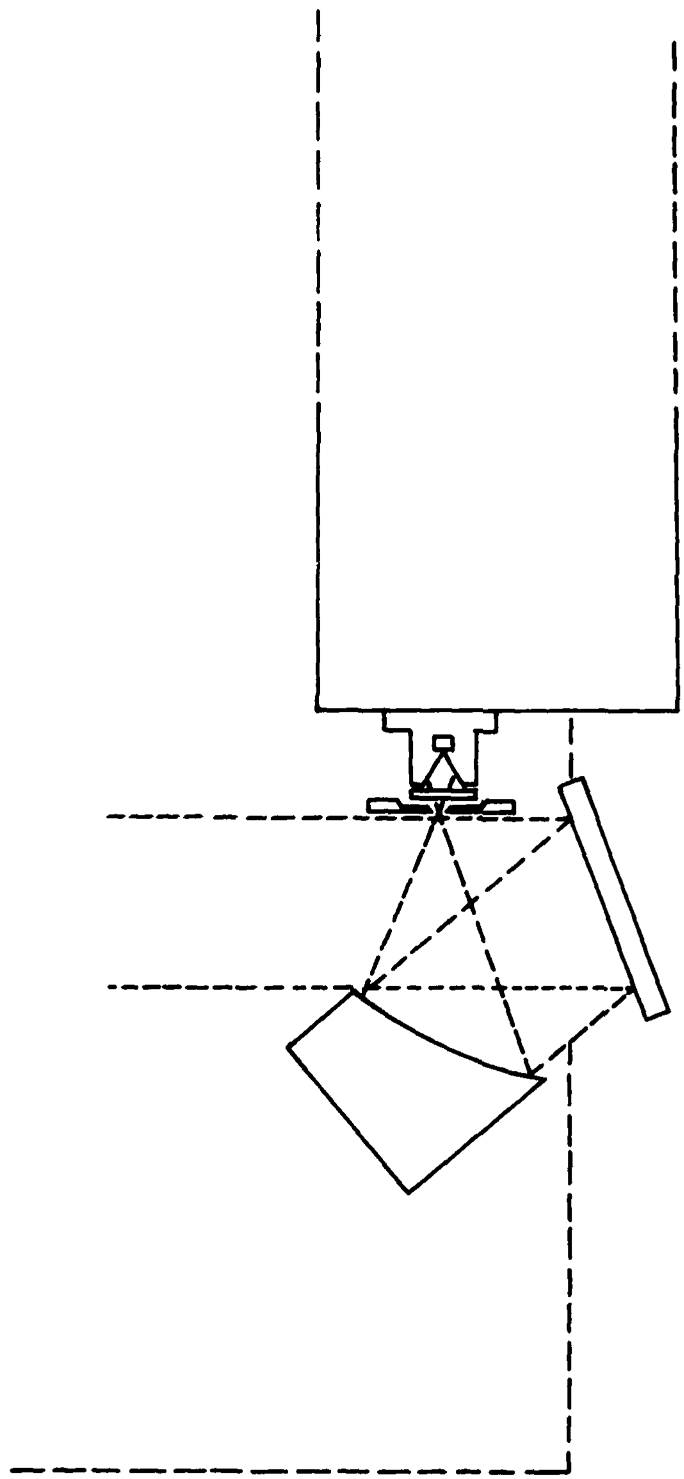

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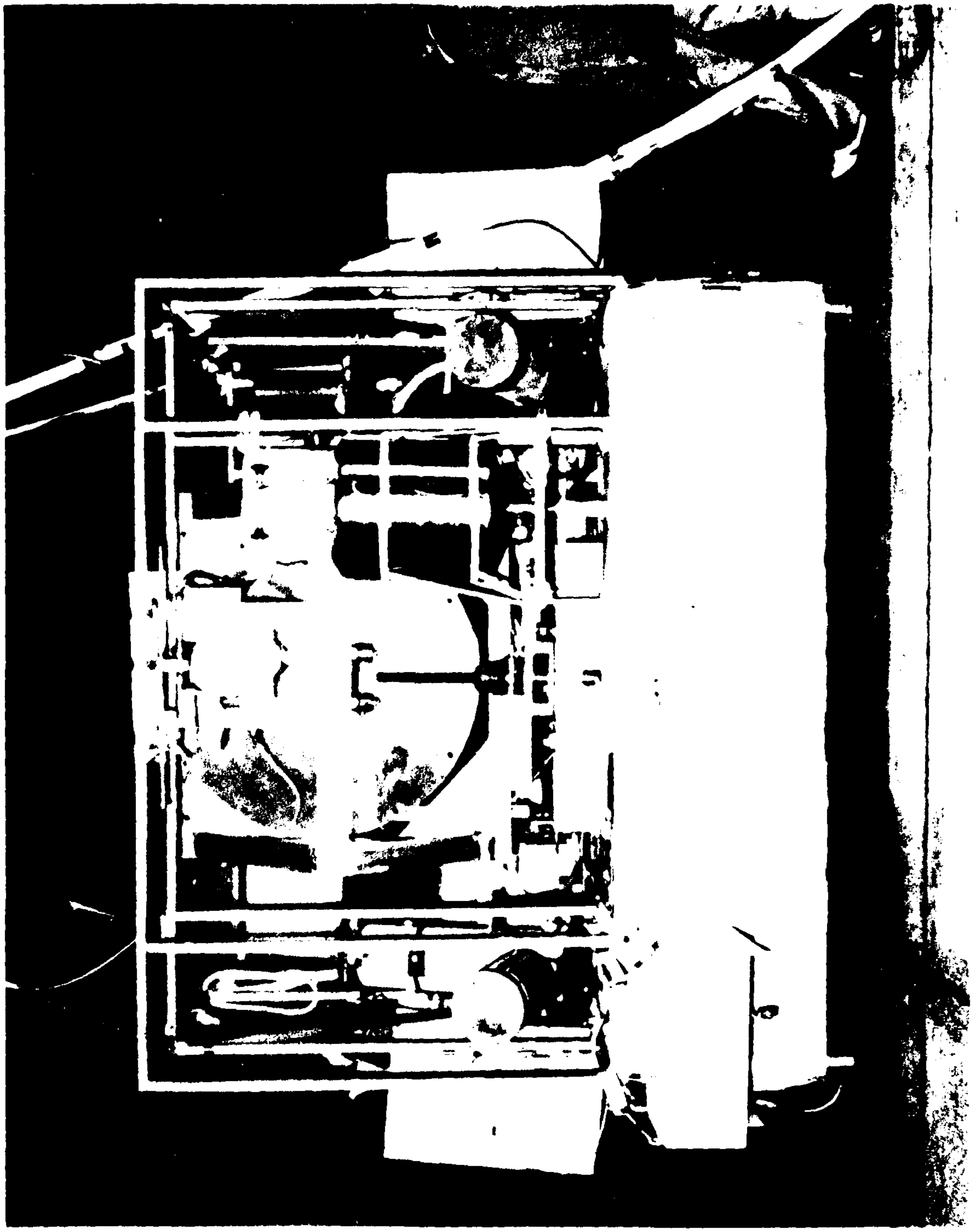

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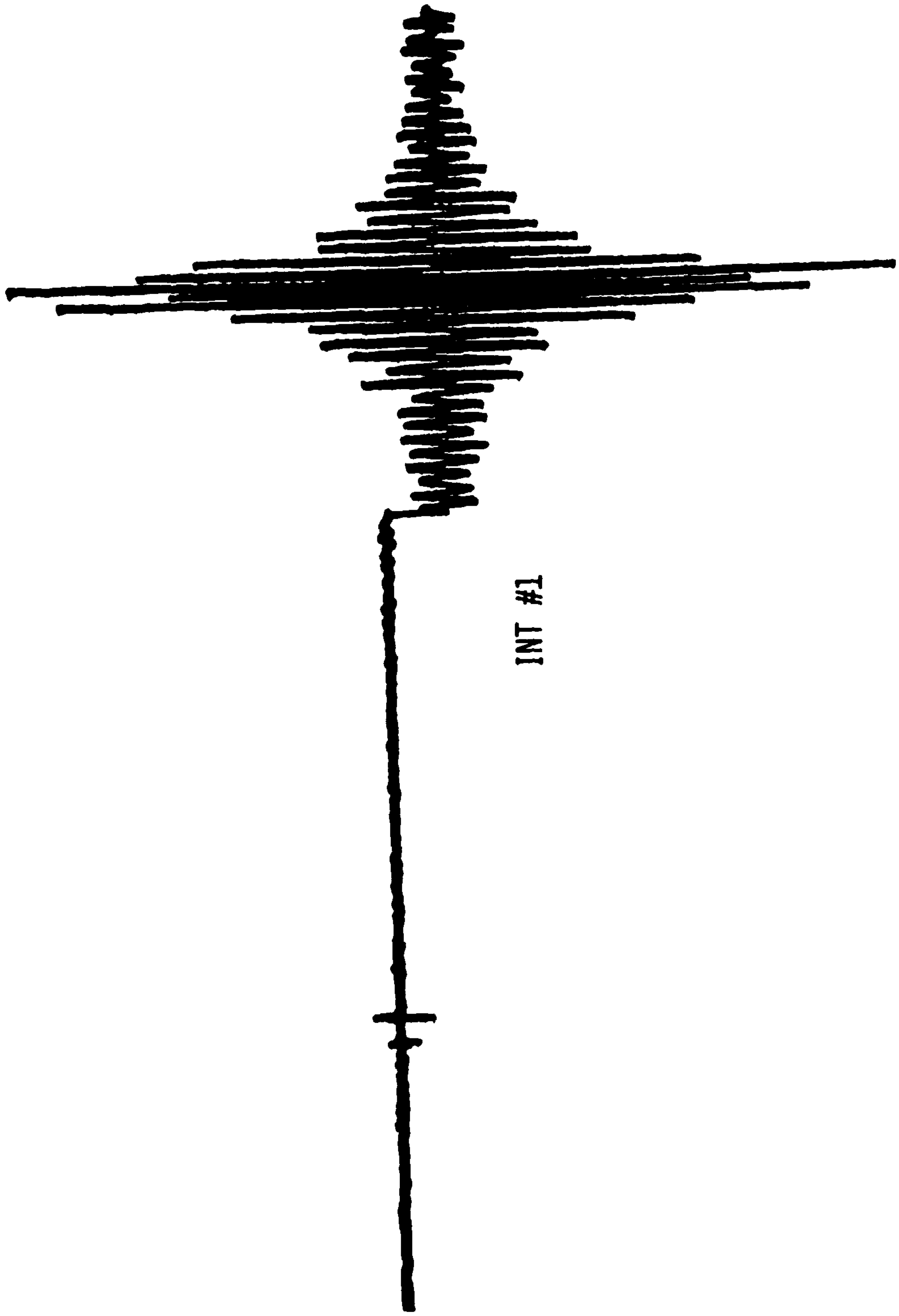
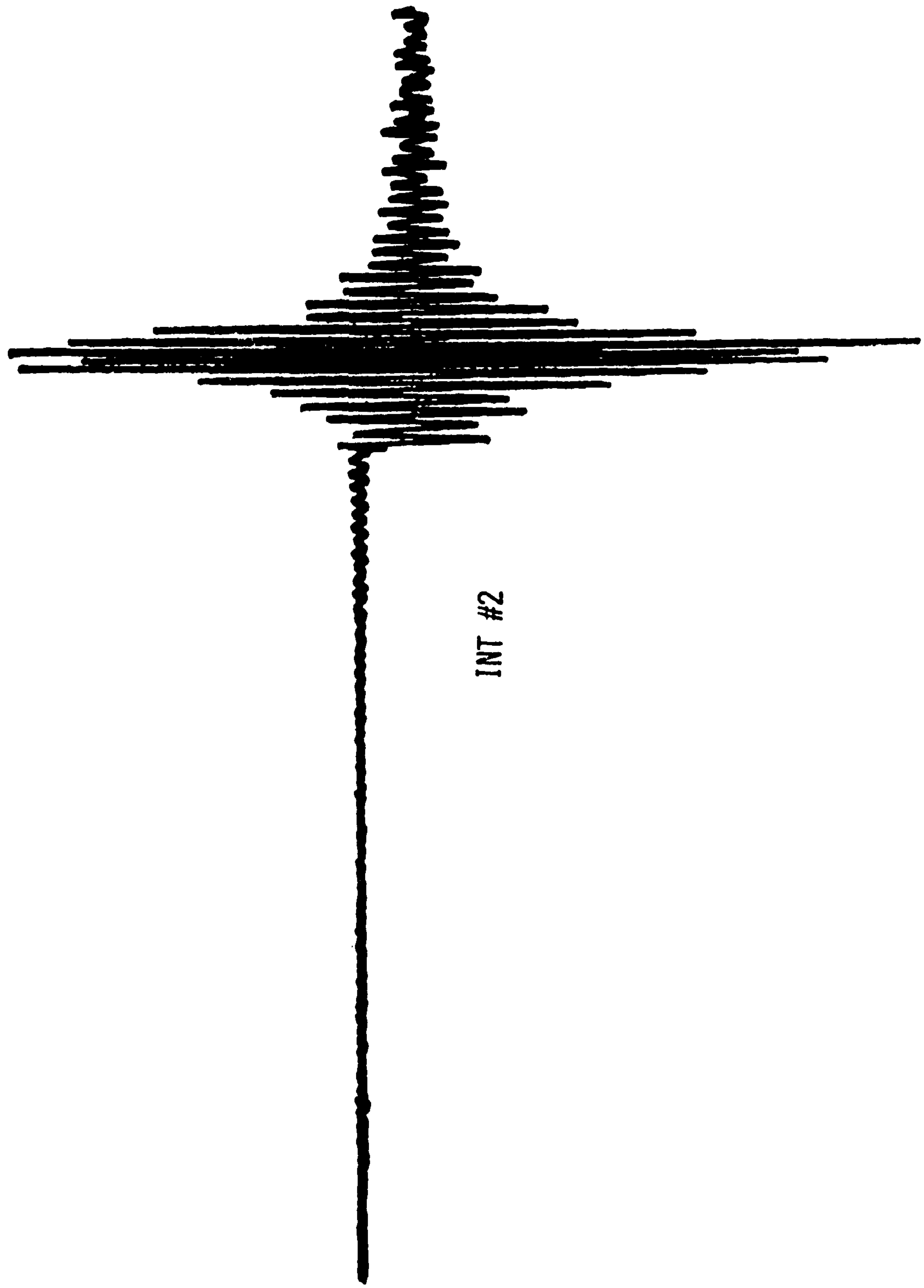


Figure 6



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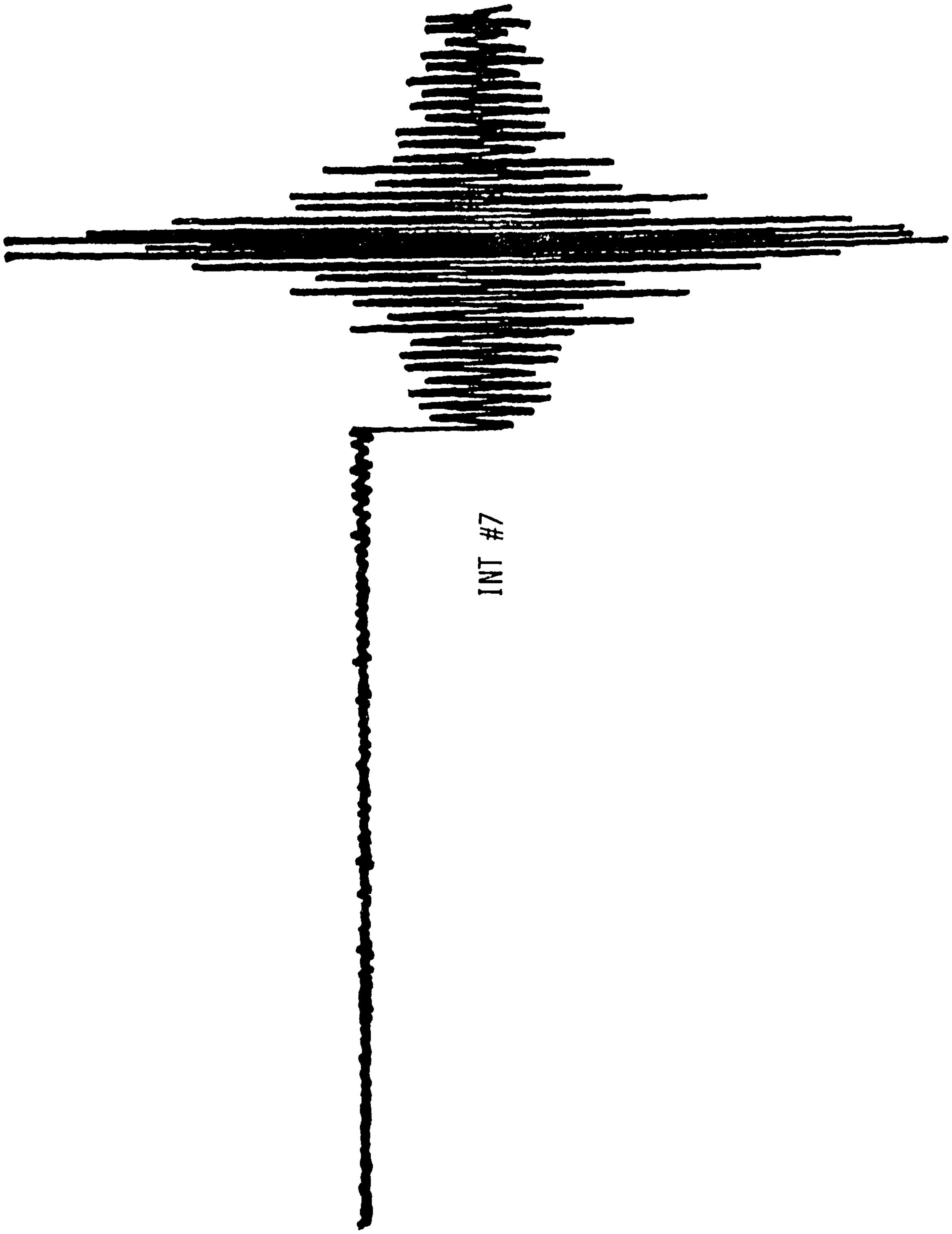


Figure 8

Atmospheric emission observed at altitude of 16,000 ft., elevation angle of 10°, and spectral resolution of 0.5 cm^{-1}

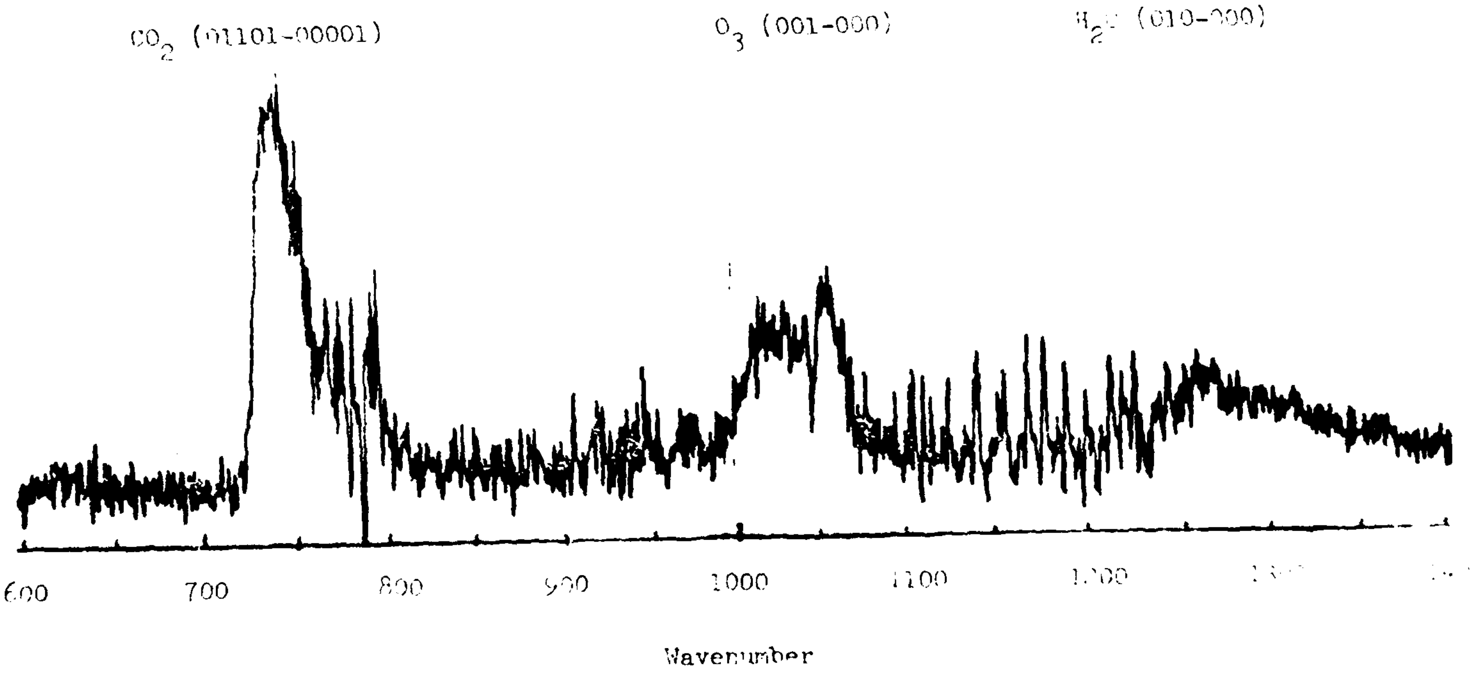
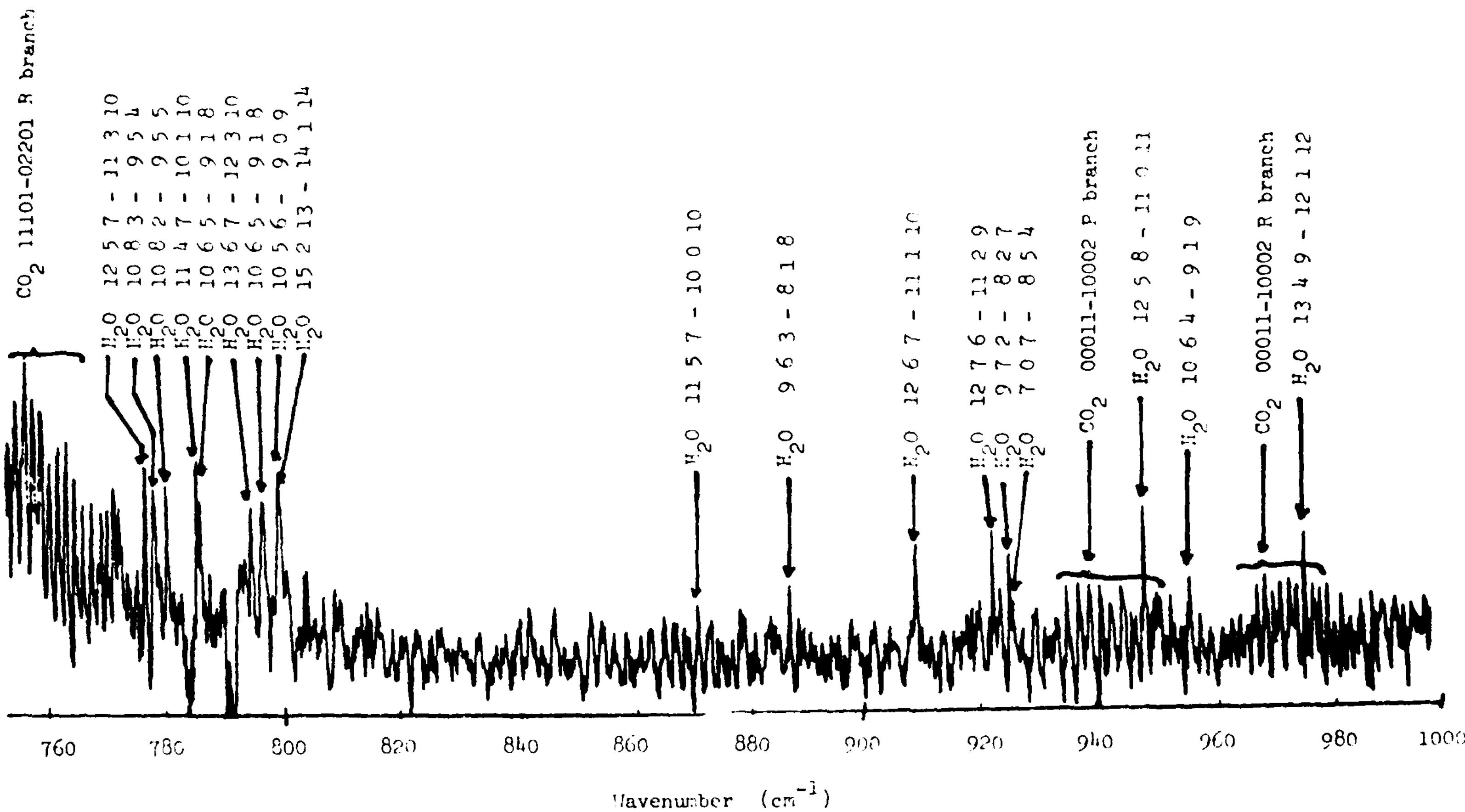


Figure 9



Atmospheric Emission: Altitude = 16,000 ft., Elevation Angle = 10°, Spectral Resolution = .1 cm^{-1}

Figure 10